NASA TECHNICAL MEMORANDUM

NASA TM X-52208

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

NASA TM X-52208

LUBRICATION AND BEARING PROBLEMS IN THE VACUUM OF SPACE

by Edmond E. Bisson
Lewis Research Center
Cleveland, Ohio

1.40

TECHNICAL PAPER prepared for presentation
(in French) at "Friction Days"
sponsored by GAMI
Paris, France, December 5-6, 1966

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1966

LUBRICATION AND BEARING PROBLEMS IN THE VACUUM OF SPACE

by Edmond E. Bisson

Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation (in French)
at "Friction Days"
sponsored by GAMI
Paris, France, December 5-6, 1966

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

[redacted]

E-3513

LUBRICATION AND BEARING PROBLEMS IN THE VACUUM OF SPACE

by Edmond E. Bisson

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

INTRODUCTION

The lubrication and bearing problems of the space age are many and varied. These problems include exposure to certain peculiarities of space such as (1) a very low ambient pressure, (2) a radiation environment, (3) the absence of a gravitional field, and (4) the presence of atomic species other than the normally encountered molecular species. The various problems, their relative importance, and some indication of research in these various areas are discussed in considerable detail in references 1 to 9. One of the major problems of any type of spacecraft involves operation of mechanisms in the vacuum of outer space. For example, such components as horizon seekers, sun or star finders, and radar antennae are involved. These components must normally operate in the high vacuum of outer space unless hermetically sealed systems are used; these sealed systems incorporate considerable complexity and weight.

The various peculiarities of the environment of space all contribute to the lubrication and bearing problems. For example, the low-pressure environment contributes to rapid evaporation of the liquid or semi-solid grease lubricants normally employed. Other problems arise because of the lack of oxygen. As is well known, lubrication ordinarily takes place by means of contaminating films between the sliding or rolling surfaces. These contaminating films can be liquids, such as the common liquid lubricants, or solid films of low shear strength. The lubrication function is, with many metals, strongly influenced by the presence or absence of oxide films on these metals. The surface oxides frequently act as protective films and, in some cases, contribute to the final surface films through either chemical reaction or chemisorption.

One of the problems at altitudes higher than 55 miles involves the fact that oxygen and nitrogen do not exist as the ordinary molecular species but rather in the atomic or ionic state. The reaction rates between most metals and atomic oxygen are markedly different from those with molecular oxygen. The influence of this different reaction rate on the friction and lubrication process in vacuum is unknown at the present time. At altitudes greater than 800 miles, atomic hydrogen and helium are the principal species present.

The main environmental change between space and the Earth's surface is, of course, that of pressure level. The absolute pressure outside the Earth's atmosphere is estimated at approximately 10^{-13} Torr, while the absolute pressure in interstellar space is estimated at approximately 10^{-16} Torr. Figure 1 shows pressure as a function of altitude. At the very low pressure levels (where a gaseous atmosphere is absent) the temperature levels will normally be dictated by radiation. Heat will be absorbed by radiation from any object that the mechanism "sees" and the mechanism will, in turn, reject heat to outer space by radiation. Various mechanisms will have different temperature levels depending upon these relative rates of heat gain and loss. It is important here to note that evaporation from surfaces is an exponential function of temperature; in consequence, the actual temperature of the mechanisms is important in this respect.

Exact duplication of the various conditions existing in space is extremely difficult. For example, the combination of radiation flux, pressure level, and proper concentration of atoms of the various gases is difficult to achieve. Some of these conditions can be simulated, however, in such a manner that their relative effects can be measured or estimated. In order to conduct meaningful experiments in a vacuum chamber, the following two requirements must be met: (1) a sufficiently low absolute pressure, and (2) precise knowledge of the gaseous species present. The normal radiation levels of the space environment are not sufficient to produce any damage to mechanical components of lubrication devices or even to conventional oil or greases.

The first requirement is predicated on the necessity for simulating a space environment with respect to evaporation of materials and for reducing oxygen concentration to such a level that formation of oxide films in the time period of the experiment is extremely unlikely. It will be recalled that oxide films can have an appreciable effect on the friction and lubrication process. Figure 2 is included to show the time required to form a hypothetical film of FeO on iron; this film is 1 angstrom thick. It will be noted that, at 25° C, FeO forms on iron in 1 minute even at oxygen pressures as low as 10^{-7} Torr. Hence, experimental data on friction and vacuum must be obtained at oxygen pressure levels lower than 10^{-7} Torr. For example, conducting friction experiments at oxygen pressure levels of 10^{-9} or 10^{-10} Torr is desirable, because a film of FeO 1 angstrom thick would require from 1 hour to 1 day to form under these conditions.

The second requirement (that of precise knowledge of the gaseous species present) is the necessity to know how closely the environment of space is approached; this requirement may be obtained by the use of a mass spectrometer. Such data in a vacuum friction apparatus have been obtained (ref. 10) from some of the friction studies conducted at the NASA laboratories. Data representative of these studies are shown in figure 3. The results show that many species are present with ion pumping, for example, hydrogen (2), nitrogen (14), oxygen (16), hydroxyl (17), water (18), carbon monoxide (28), nitrogen (28), and carbon dioxide (44). (The numbers in parenthesis are the ratio of molecular weight to charge.) Figure 3 shows the reduction of detectable gases by various techniques to the point where only hydrogen is present when liquid helium is used to cryopump the chamber after bakeout at 93° C and gaseous nitrogen purge.

EVAPORATION RATES IN VACUUM

The Langmuir equation for rate of evaporation is $G = \frac{P}{17.14}\sqrt{\frac{M}{T}}$, where G is the rate of vaporization (g/(sq cm)(sec)), P is vapor pressure (mm Hg), M is molecular weight, and T is temperature ($^{\circ}$K). The vapor-pressure equation can be written as follows: $P = Ce^{-L/RT}$, where C is a constant, L is the heat of vaporization, and R is the gas constant. The Langmuir equation is based on the assumption that all the atoms that evaporate from the surface are lost permanently; that is none of the atoms are reflected back to the surface to permit possible recondensation. The Langmuir equation thus yields the maximum rate of loss.

Oils and greases are normally used as lubricants. At low pressures and at temperature extremes, metals and inorganic compounds are of interest for use as lubricants. The evaporation rates of these materials in vacuum are needed.

Oils and Greases

The evaporation rates for various oils and greases were determined under vacuum conditions (approx. 10^{-7} Torr) at various temperatures by Buckley, Swikert, and Johnson (ref. 6). These results are presented in figure 4. Mil-L-7808 is the synthetic lubricant in common use in aircraft turbine engines; mineral oils of two different viscosities are included in figure 4 as well as greases of various compositions.

An arbitrary limit of 10^{-7} gram per square centimeter per second was set on the evaporation rate; values greater than this were considered excessive. While this choice was arbitrary, it is based on the fact that a boundary lubricating film of liquid 20 molecular layers thick will evaporate in less than 1 minute. On this basis, none of the materials in figure 4 are satisfactory at temperatures of 90° C or greater.

Metals

Evaporation rates for various metals were determined in vacuum over the range of temperatures from 13° to 540° C (ref. 6). The results of this investigation are presented in figures 5(a) and (b). Also presented in figure 5(a) are calculated evaporation rates based on measured vapor-pressure data from the literature. These calculated curves are the solid lines. The experimental data of the investigation of reference 6 are shown as the individual data points. In general, there is very good agreement between calculated and measured evaporation-rate data. On the basis of the evaporation-rate data of figure 5(a) and (b), a number of metals are of interest including gallium (5(b)), which will be discussed in more detail later.

Inorganic Coatings

In order to interpret the evaporation rates of solid-film lubricant coatings, evaporation-rate data were obtained for the constituents of the coating as well as for the final coatings themselves. The data for compressed disks of various lubricant coating constituents are presented in figure 6. One important result from these experiments was the finding that some of the materials (such as NiF and PbO) dissociated at the higher temperatures.

The evaporation rates for MoS_2, WS_2, CaF_2, and BaF_2 at temperatures from 13° to 540° C are shown in figure 7. In general the evaporation rates of all materials in vacuum are quite low, even at elevated temperatures. These materials, therefore, appear to be the most stable of the inorganic substances examined by the authors of reference 6. Evaporation rates were also obtained for finished MoS_2 coatings with various binders (ceramic, silicon resin, and phenolic epoxy). The results of these evaporation-rate experiments showed that the rate for all coatings was relatively low.

Polymers

Evaporation rates of other materials were checked also. For example, the evaporation rate of Teflon was reasonably low at temperatures below the decomposition temperature of approximately 288° C. A recent polymer development that appears very attractive for space lubrication applications is that of the polyamides. These materials have very low evaporation rates and have good friction and wear characteristics in vacuum (ref. 11).

FRICTION AND WEAR IN VACUUM

As previously mentioned, one of the most important adverse effects of the low pressures in space is the removal of surface films by evaporation. If the surfaces become sufficiently clean, severe adhesion and welding can occur between sliding surfaces. Since materials under such conditions will have a tendency to rub together in their "virgin" states, it would be desirable to avoid this condition where possible by providing a contaminating film with lubricants of various types.

Unlubricated Metals

Friction and wear experiments were conducted in air and in vacuum with five alloy combinations in the unlubricated state. The results are shown in figure 8. The results for the iron-base alloy 52100 sliding on 52100 appear to contradict the results of reference 12, which shows that operation of metals in vacuum increased the friction coefficient markedly. It should be noted that the specimens in these experiments were not outgassed and, hence, had some oxide films on them. The reduction in friction coefficient under vacuum conditions for the 52100 specimens may possibly be the result of the formation of oxides of iron lower than the normal Fe_2O_3; these lower oxides are FeO and Fe_3O_4. These lower oxides have been shown (ref. 13) to be beneficial from the standpoint of friction and wear. Figure 9(a) shows the friction of 52100 sliding on 52100 as a function of the ambient pressure in the chamber. This pressure was varied from atmospheric to 2×10^{-7} Torr. The friction coefficient at atmospheric pressure is approximately 0.45 and decreases to a minimum of approximately 0.2 at 10^{-2} Torr, after which it increases to about 0.38 at 2.0×10^{-7} Torr. These results are explained by the formation of the beneficial iron oxides FeO and Fe_3O_4 at the intermediate pressure levels. At pressure levels of 10^0 to 10^{-6} Torr, the beneficial oxides would have a tendency to form because of the limited availability of oxygen atoms. The results shown in figure 9(a) were later confirmed by Reichenbach, et al. (ref. 14) for different steel specimens over the same pressure range. Even at a pressure level of 10^{-7} Torr, the oxygen concentration is sufficient to form the beneficial, lower iron oxides. Hence, experiments were made with lower concentrations of oxygen.

Figure 9(b) shows the results of experiments conducted on 52100 sliding against 52100 under a pressure of 10^{-7} Torr obtained by cryopumping. In this case, a liquid-helium condensing coil inside the vacuum chamber condensed the condensible gases such as nitrogen and oxygen. In this manner, the authors of reference 6 felt that the availability of oxygen atoms would be markedly reduced. Figure 9(b) confirms their belief. Friction coefficient as a function of time showed a slight increase from the initial value of 0.3 to the value of about 1.0 at 30 minutes. At 30 minutes, the friction coefficient rose markedly to a value of about 4, after which it continued rising until the specimens welded so firmly together that the drive motor of the mechanism was stalled. The initial low friction coefficient is believed to be the result of the presence of the beneficial low oxides of iron (FeO and Fe_3O_4). The time during which the friction coefficient remained relatively low (i.e., less than 1.0) represents the time required to wear these beneficial oxides from the surface. After the oxide film has been worn from the surface, it could not re-form because of the limited availability of oxygen atoms. Hence, complete and total failure of surfaces took place.

Crystal Structure

Recent work in vacuum lubrication at the NASA Lewis Research laboratories indicates a marked difference in friction and wear between metals of the cubic and hexagonal crystal structures (ref. 15). Figure 10 shows the atomic arrangement in typical face-centered-cubic and hexagonal crystal lattices. Polycrystalline metals are agglomerates of crystallites that have these basic forms; when welding occurs between two metals, the weld is made up of these crystals. When the crystals in the welds shear, they do so along distinct planes, and the required shear force depends on the plane being sheared. Shear forces in cubic crystals are normally greater than corresponding shear forces in hexagonal crystals because of work hardening of cubic crystals and orientation on planes of easy slip in hexagonal metals. In hexagonal crystals, shear forces are usually the least on the basal plane (i.e., when shear occurs in a plane parallel to the hexagons). This shearing process is illustrated in figure 11, which shows the top hexagonal plane of the crystal displaced from the normal axis during the shear deformation process.

As surfaces are moved with respect to one another, deformation, shear separation, and recrystallization occur as a continuing process.

The data in figure 12 showed the difference in force required to shear metals of cubic and hexagonal structures. The crystal form of cobalt at normal temperatures is hexagonal. However, cobalt transforms from the hexagonal to the cubic structure when heated above 400° C. A marked increase in friction is shown to accompany this crystal transformation (fig. 12). At low temperatures, the sliding is of hexagonal cobalt on hexagonal cobalt. At the higher temperatures, the sliding is of cubic cobalt on cubic cobalt. The transition from hexagonal to cubic is shown at less than 400° C because frictional heating caused the surface temperatures to be somewhat higher than the bulk metal temperatures measured. Adhesive wear rate was about 100 times greater for the cubic cobalt than for the hexagonal cobalt as indicated by the two wear rates shown in figure 12. Furthermore, at the highest temperature, complete welding of the specimen occurred. These data suggest that sliding metals should be used in the hexagonal crystal form over the entire operating temperature range.

Additional inquiry showed that the shear force in hexagonal crystals varies with the relative spacing of the atoms within the crystal. In particular, the shear force is controlled by the ratio of the distance c (the spacing between hexagonal planes) to the distance a (the spacing between adjacent atoms in the hexagon). Various metals with hexagonal crystal structures have different values of c/a. Figure 13 shows the variations of friction in vacuum for some of these metals.

The coefficient of friction declines with increasing c/a, and those metals that showed low friction gave no evidence of gross surface welding.

Of the various metals in this study, cobalt and titanium are more commonly used and available and, hence, are of the greatest practical interest. Titanium is well known as a metal subject to severe welding or galling and otherwise having very poor friction properties. On the other hand, cobalt alloys have been used in bearings, but usually in alloys with predominately cubic structure. The preceeding study on crystal structure effects suggested that improved friction properties could be obtained if cobalt and titanium were alloyed in such a way as to stabilize the hexagonal structure over a greater range of temperature and to increase the c/a lattice ratio for titanium. This is necessary for titanium because its poor friction properties can be related to shear and slip mechanisms which, in turn, can be related to c/a lattice ratio (ref. 16).

Simple binary alloys of titanium with either tin or aluminum were found to provide the desired structural characteristics. Figure 14 shows friction and lattice ratio for a series of titanium-aluminum and titanium-tin alloys. Increasing the percentage of aluminum or tin produced a number of results: (1) higher c/a ratios, (2) greatly reduced friction, and (3) minimized surface failure tendencies.

Influence of Other Physical Properties

There are other physical properties of metals that influence friction and wear behavior in a vacuum environment. These include order-disorder reactions, orientation of crystallites, and chemical affinity of sliding couples. In reference 17 it has been shown that copper-gold alloys exhibit superior friction properties when compounds of these two elements are in the ordered state. Studies with single crystals of various metals (Co, Ti, Be, W, and Cu) and inorganic compounds have shown that crystallographic planes and directions of greatest atomic density exhibit the lowest coefficients of friction when the clean surfaces are sliding in vacuum. Further, for metals sliding on inorganic compounds, where chemical reaction between the metal and the inorganic compound can occur, shear and friction may be dictated by the type of bonds formed.

Solid-Film Lubricant Coatings

Friction and wear experiments were conducted on a number of solid-film lubricant coatings (ref. 6). The friction and wear results for various MoS_2 films in vacuum are presented in figure 15. From these results, it is apparent that the binder material plays some role in the friction and wear process. All coatings, with the exception of the ceramic-bonded coatings, showed good results. The ceramic-bonded coating is, however, basically a high-temperature coating.

Figure 16 shows the results of experiments with other lubricant coatings. These coatings include two coatings developed particularly for high temperature use in air (lead oxide - silicon dioxide ($PbO-SiO_2$), and calcium fluoride (CaF_2). Coatings in figure 16 also encompass the soft metals: tin, gold, lead, and silver. All coatings have been used as lubricants under vacuum conditions in the past. All coatings showed reasonable friction coefficients, although the wear is considerably higher than was the wear for the MoS_2 coatings of figure 15.

Gallium Films

One of the materials of promise as a possible lubricant in the vacuum environment of space is gallium (ref. 18). For use as a space lubricant, a liquid lubricant should (1) have low vapor pressure in order that it may remain on the surface for long periods of time, (2) be liquid over a broad temperature range, and (3) have good wetting properties. Gallium possesses all these characteristics; it has very low vapor pressure to 540° C (as shown in fig. 5(b)), has a liquidus range of 30° to 1982° C, and will wet nearly all surfaces. One major problem associated with gallium as a lubricant is its extremely reactive nature toward other metals; it has a strong tendency to form alloys or solid solutions.

Gallium films can be applied to surfaces in a number of ways. In order to study the effects of application techniques on friction and wear, the first experiments with gallium were conducted in air. The results of these experiments are shown in figure 17, which compares friction and wear of four different gallium films with each other and with an unlubricated specimen. Of these various films, the pretreated film appears most practical; the 260° C pretreatment was chosen because of its better results. All further experimental results on pretreated gallium films will refer to the 260° C pretreatment.

Results of experiments in vacuum with various unlubricated material combinations and with the same combinations lubricated with a pretreated gallium surface film are presented in figure 18. These experiments were conducted at a pressure level of 10^{-8} Torr. The results show that, for all the material combinations, wear and friction with a pretreated gallium surface film are much less than for the unlubricated combination. For example, with the combination 440-C on 440-C, wear with the gallium lubricated specimens is only 1/10,000 that of the unlubricated specimen.

ROLLING-ELEMENT BEARINGS IN VACUUM

The rolling-element bearing appears particularly promising for use in space where the problem of lubrication can be critical because this type of bearing has very little sliding and, therefore, inherently requires very little lubricant. With this type of bearing, however, sliding as well as rolling occurs in the contact region between the rolling elements and the races. Therefore, lubrication must be supplied for adequate and reliable operation.

Since the rolling-element bearing requires very little lubricant for lubrication, it is possible for short-time applications to use such bearings lubricated with either liquids or greases, provided that these lubricants have low vapor pressure. Adequate sealing by the use of double-shielded bearings should be of some help in this respect. Some bearing experiments at pressures of the order of 10^{-5} to 10^{-6} Torr have been reported (refs. 3, 7, and 19 to 22).

Experiments on liquid- or grease-lubricated bearings indicated that a chlorinated silicone oil or a grease made with the chlorinated silicone seemed to give relatively good performance. Experiments were conducted by the authors of references 21 to 23 on ball bearings that incorporated self-lubricating containers. Some of these retainers were made of various combinations of Teflon with glass fiber or with metals (ref. 21). Other retainers were plated with thin metallic films such as gold (ref. 22).

Some studies were conducted with ball bearings larger than the normal instrument size bearings; 20-millimeter-bore ball bearings were investigated by the authors of reference 23. They used porous nonmetallic retainers that had been vacuum impregnated with various types of oils. This type of bearing is lubricated by flow of liquid out of the porous retainer as the bearing operates. For these relatively large bearings, lubrication by the retainer impregnation technique was found to be somewhat inadequate under the conditions of their investigation. Their results indicated that the flow of lubricant out of the impregnated retainer was not fast enough to provide adequate lubrication.

Tiros II Bearings and Seals

An interesting application of the rolling-element bearings in a "semi-sealed" system was made to the Tiros II satellite. Tiros II is a weather satellite designed for relatively short-time operation. The mechanism for the satellite was a ". . . 5-channel radiometer. . . . [this] system consists of five optical mirrors mounted on five gears and eight ball bearings. . .". A schematic of the system is shown in figure 19. The requirements for the bearings were rather severe: (1) precise alignment of the optical mirror was necessary, (2) low starting and running torque, and (3) reliability. Output torque of the motor driving the five mirrors (through gearing) and eight ball bearings was only 0.03 inch-ounce. This entire mechanism was designed by using the principle of "molecular flow" seals. These are non-rubbing seals for which the leakage can be calculated precisely by utilizing the kinetic theory of gases and the Knudsen principle.

The radiometer spindle assembly described in reference 7 was designed on the basis of minimum loss of lubricant by evaporation. This design was based on the fact that, on a molecular scale, even smooth surfaces appear rough, and according to Knudsen (ref. 24), the direction in which a molecule rebounds after a collison with a wall is statistically independent of the angle of incidence. For this reason, the molecular flow resistance of small orifices can be made relatively high. The vapor pressure inside the chamber can be maintained, and vaporization of the lubricant can be minimized.

The bearings in the mechanism in reference 7 were so designed to employ lubricant reservoirs of oil-impregnated sintered nylon (fig. 19). The lubricant employed was a Mil-L-6085A diester oil with a vapor pressure of approximately 10^{-4} Torr. When the outside pressure reaches a value below 10^{-2} Torr, molecular flow occurs around the shaft through the small clearance. The clearance was maintained at a nominal 0.0005 inch. Weinreb indicates that, with the aid of an equation derived by Knudsen and others, it is possible to calculate the escape rate of oil from the bearing assembly. This information can then be used to design a bearing for space application for the required life. The validity of this approach was confirmed since Tiros II operated successfully for approximately 9400 hours.

SUMMARY

It can be stated that actual conditions of space are not precisely known; duplication of conditions is therefore difficult, but simulation is possible. The desirable pressure level for lubrication experiments is 10^{-9} Torr or less. Evaporation rate of materials is very important since evaporation will remove the contaminating (lubricant) films from

the surface permitting contact of clean surface and, hence, severe wear and friction. Low evaporation rates are obtained with some metals (silver, tin, gallium), some lubricating compounds (MoS_2, PbO, SiO_2, and CaF_2), as well as with Teflon. Friction and wear experiments with various lubricant coatings in vacuum show that MoS_2 and other films (various compounds, plated metals, etc.) appear promising; of these MoS_2 showed the lowest friction and wear over short time periods.

Experiments with instrument size bearings in vacuum show good results with silicones and silicone greases as the lubricant. Other experiments have been done with self-lubricating cages or retainers, and reasonably successful operation has been obtained. Successful operation in space of a mechanism was obtained on an actual satellite (Tiros II). Lubrication was based on controlled loss of lubricant from a reservoir; this controlled loss was precalculated on the basis of a "molecular flow resistance" equation.

Finally, vacuum friction studies have been proved useful to explore effects normally hidden because of the usual presence of oxides in air. An example of this is crystal structure. The results in vacuum show that hexagonal structures frequently showed better frictional properties than cubic structures. The controlling variable for the friction of hexagonal metals appears to be the lattice ratio c/a. Improvement in the frictional properties of a normally poor friction material, titanium, were obtained by alloying the titanium with either aluminum or tin in order to increase the c/a ratio. The binary alloys of titanium with aluminum or tin showed increases in the c/a ratio and appreciable decreases in both friction coefficients and surface welding tendencies.

REFERENCES

1. Bisson, Edmond E.; and Anderson, William J.: Advanced Bearing Technology. NASA SP-38, 1964.

2. Atkins, J.H.; Bisplinghoff, R.L.; Ham, J.L.; Jackson, E.G.; and Simons, J.C.,Jr.: Effects of Space Environment on Materials. Res. Proj. 40-1-041, Nat. Res. Corp., Aug. 15, 1960.

3. Clauss, F.J.: Lubricants and Self-Lubricating Materials for Spacecraft Mechanisms. LMSD-894812, Lockheed Aircraft Corp., Apr. 18, 1961.

4. Lad, Robert A.: Survey of Materials Problems Resulting from Low-Pressure and Radiation Environment in Space. NASA TN D-477, 1960.

5. van Vliet, R.M.: A Molecular Approach to Dry Film Lubrication in a Vacuum (Space) Environment. TR 59-127, WADC, July 1960.

6. Buckley, D.H.; Swikert, M.; and Johnson, R.L.: Friction, Wear and Evaporation Rates of Various Materials in Vacuum to 10^{-7} mm Hg. ASLE Trans., vol. 5, no. 1, Apr. 1962, pp. 8-23.

7. Weinreb, Marius B.: Results of Tiros II Ball Bearing Operation in Space. Meteorology Branch, Goddard Space Flight Center, NASA, Wash. 25, D.C., Mar. 1961.

8. Johnson, Robert L.; and Buckley, Donald H.: Lubricants and Mechanical Components of Lubrication Systems for a Space Environment. NASA TM X-52031, 1964.

9. Proceedings of Space Lubrication Conference, 3 May 1963, DOD FL 210/53, Sept. 1963.

10. Buckley, Donald H.; and Johnson, Robert L.: Influence of Microstructural Inclusions on Friction and Wear of Nickel and Iron in Vacuum to 10^{-9} Millimeter of Mercury. NASA TN D-1708, 1963.

11. Buckley, D.H.: Friction and Wear Characteristics of Polyimide and Filled Polyimide Compositions in Vacuum (10^{-10} mm Hg). NASA TN D-3261, 1966.

12. Bowden, F.P.; and Tabor, D.: The Friction and Lubrication of Solids. Clarendon Press (Oxford), 1950.

13. Johnson, Robert L.; Godfrey, Douglas; and Bisson, Edmond E.: Friction of Solid Films on Steel at High Sliding Velocities. NACA TN 1578, 1948.

14. Reichenbach, G.S.; Shaw, R.,Jr.; and Foster, R.G.: Lubrication Behavior in High Vacuum. ASLE Trans., vol 7, no. 1, Jan. 1964.

15. Buckley, Donald H.; and Johnson, Robert L.: Friction and Wear of Hexagonal Metals and Alloys as Related to Structure and Lattice Parameters in Vacuum to 10^{-10} Millimeter of Mercury. ASLE Trans., vol. 9, no. 2, 1966.

16. Buckley, D.H.: Influence of Crystal Orientation on Friction Characteristics of Titanium Single Crystals in Vacuum. NASA TN D-2988, 1965.

17. Buckley, Donald H.: Influence of Order-Disorder Transformation on Friction Characteristics of Copper-Gold Alloys in Vacuum, NASA TN D-2985, 1965.

18. Buckley, D.H.; and Johnson, R.L.: Gallium Rich Films as Boundary Lubricants in Air and in Vacuum to 10^{-9} mm Hg. ASLE Trans., vol. 6, no. 1, Jan. 1963, pp. 1-11.

19. Freundlich, M.M.; and Hannan, C.H.: Problems of Lubrication in Space. Lubrication Eng., vol. 17, no. 2, Feb. 1961, pp. 72-79.

20. Corridan, R. E.: Summary Report: Bearing and Lubrication Study. Advanced Tech. Lab. Div., Am. Standard Corp., June 30, 1959.

21. Bowen, Paul H.: Dry Lubricated Bearings for Operation in a Vacuum. ASLE Trans., vol. 5, no. 2, Nov. 1962, pp. 315-326.

22. Evans, Harold E.; and Flatley, Thomas W.: Bearings for Vacuum Operation. Phase I. NASA TN D-1339, 1962.

23. Smith, L. Dale; Glenn, Dean C.; and Scibbe, Herbert W.: Evaluation of Impregnated Lubricants in Ball-Bearing Retainers at 10^{-6} Torr. NASA TN D-3259, 1966.

24. Knudsen, M.: Kinetic Theory of Gases; Some Modern Aspects. Third ed., Methuen, London (England), 1950.

25. Jastrom, Robert: Lunar and Terrestrial Atmospheres. Vol. 5 of Advances in Aero. Sci., Plenum Press, Inc., 1960, pp. 338-345.

E-3513

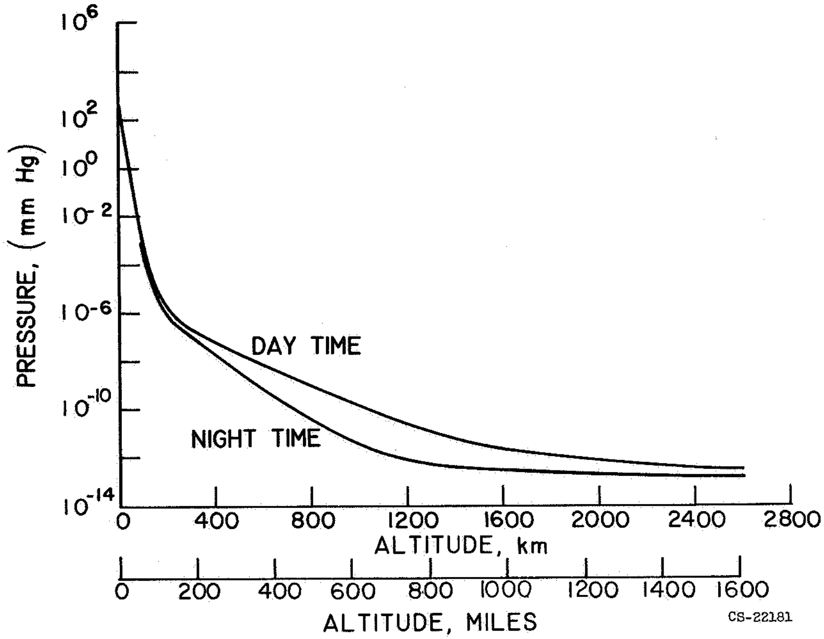


Figure 1. - Pressure as a function of altitude (from ref. 25).

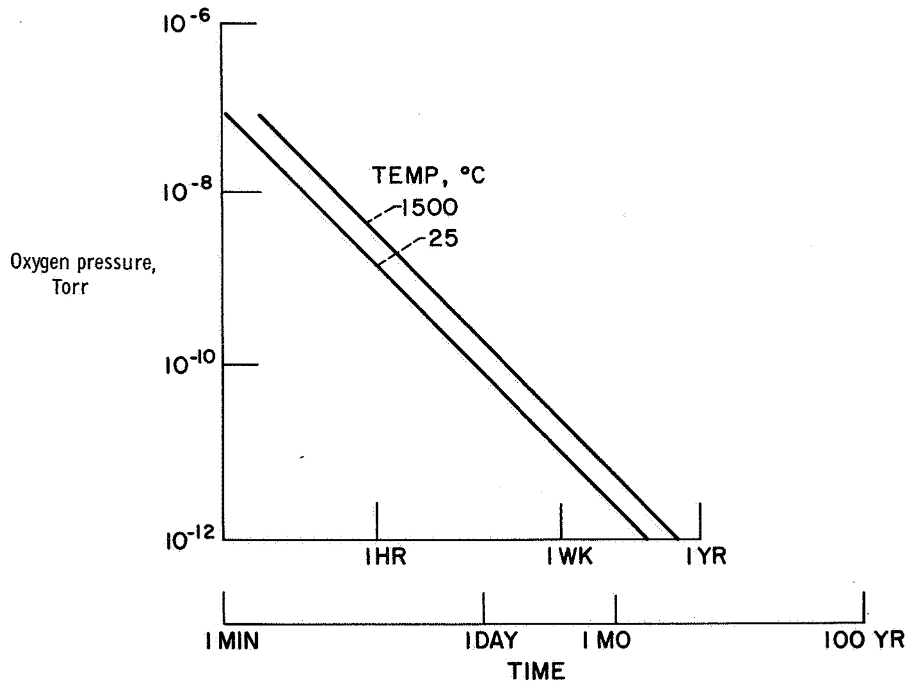


Figure 2. - Time required to form hypothetical 1-angstrom-thick film of FeO on iron. (from ref. 2).

E-3513

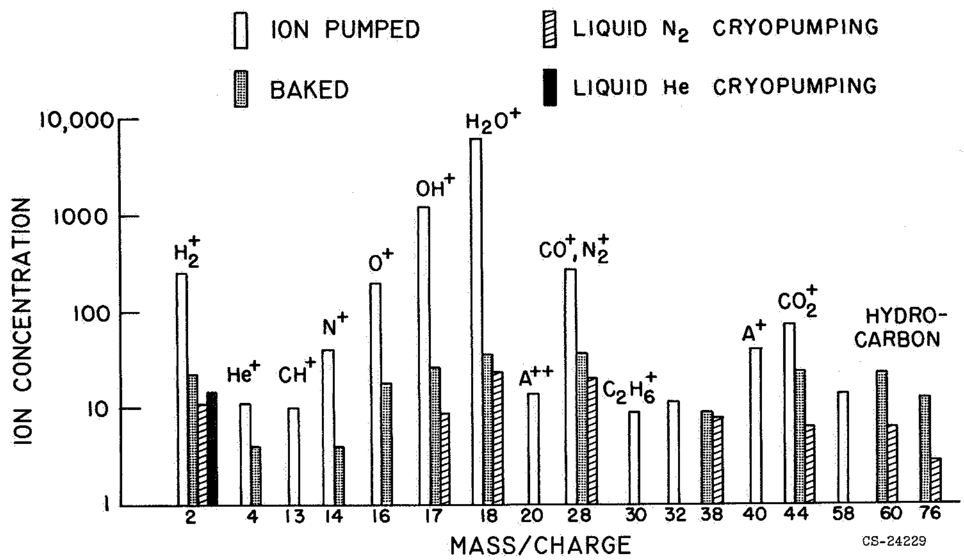


Figure 3. - Ion-pumped vacuum system (mass spectrometer data).

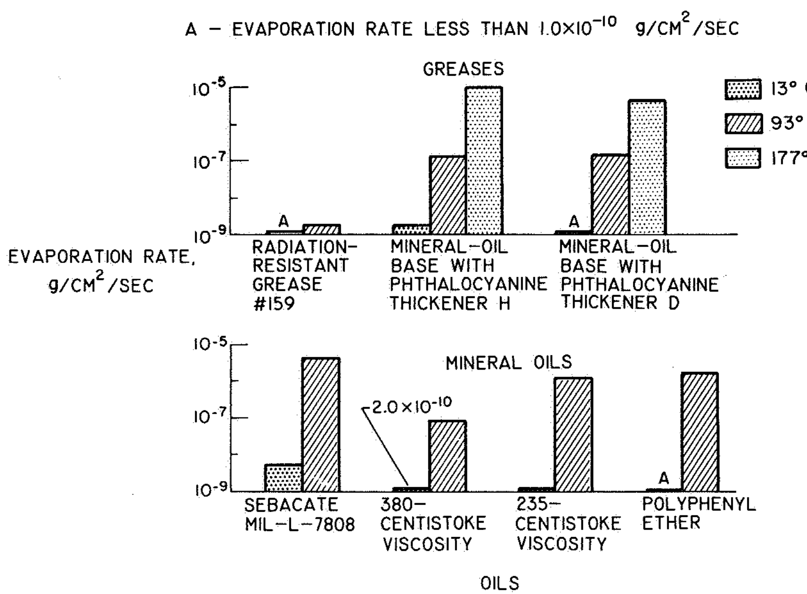


Figure 4. - Evaporation rates for various oils and greases in vacuum. Ambient pressure, 10^{-6} Torr.

E-3513

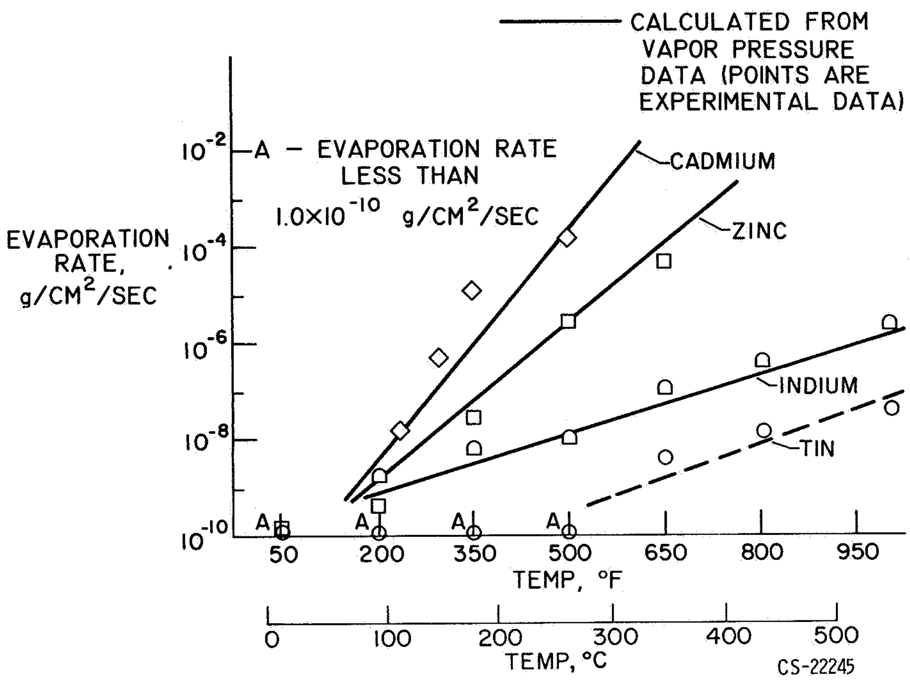


Figure 5(a). - Evaporation rates for various metals in vacuum. Pressure, 10^{-6} Torr (ref. 6).

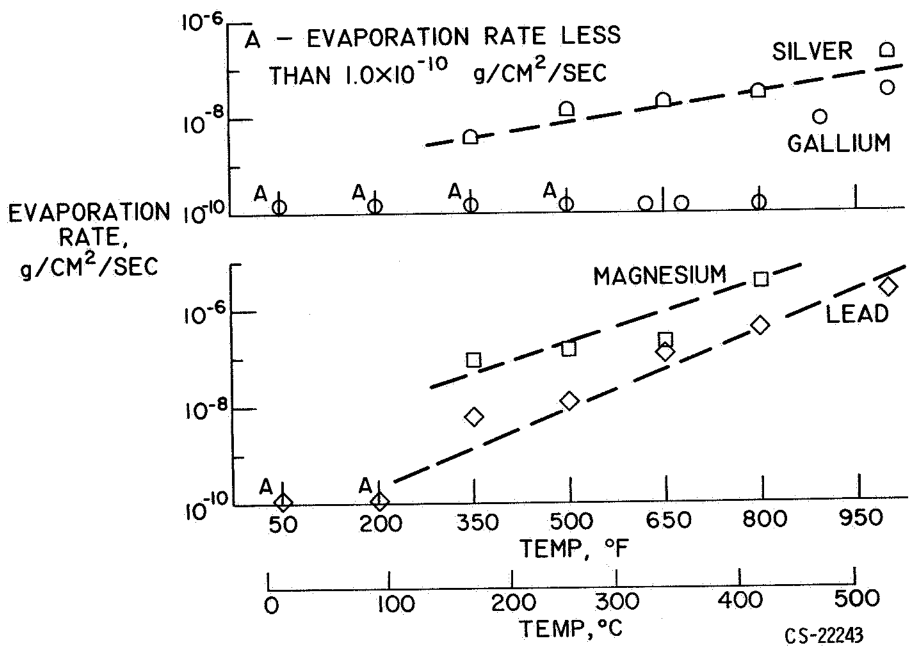


Figure 5(b). - Evaporation rates for various metals in vacuum. Pressure, 10^{-6} Torr (refs. 6 and 18).

E-3513

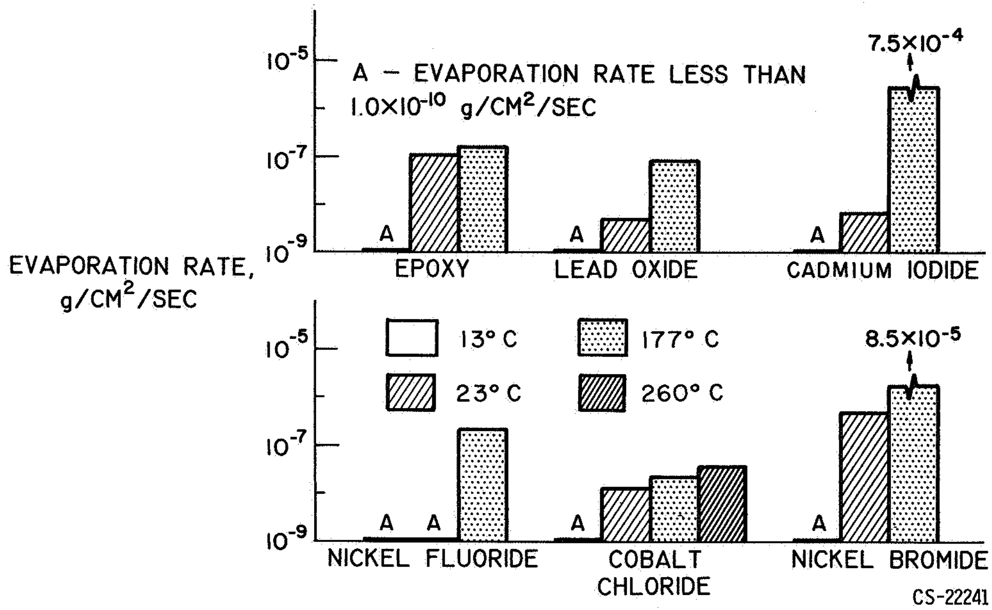


Figure 6. - Evaporation rates for possible coating constituents in vacuum. Ambient pressure, 10^{-6} Torr.

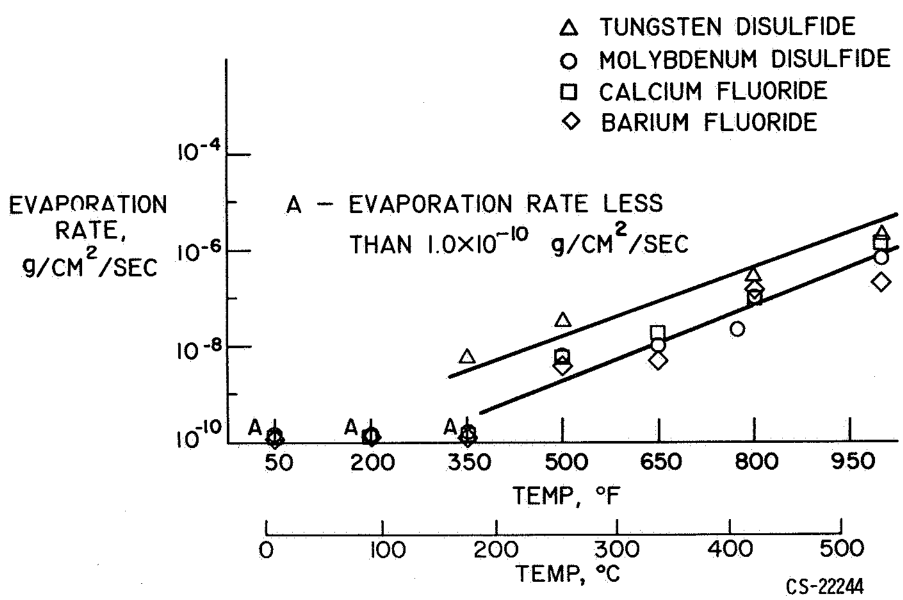


Figure 7. - Evaporation rates for inorganic compounds in vacuum. Pressure, 10^{-6} Torr (ref. 6).

E-3513

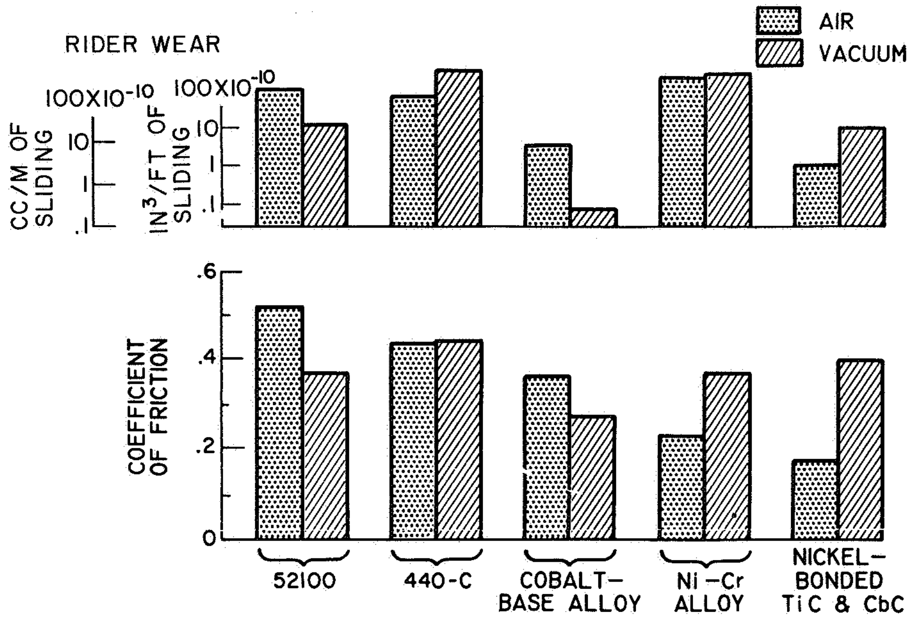


Figure 8. - Friction and wear of various alloys in air and in vacuum. Pressure, 10^{-6} Torr; sliding velocity, 197 centimeters per second; load, 1000 grams; duration of run, 1 hour.

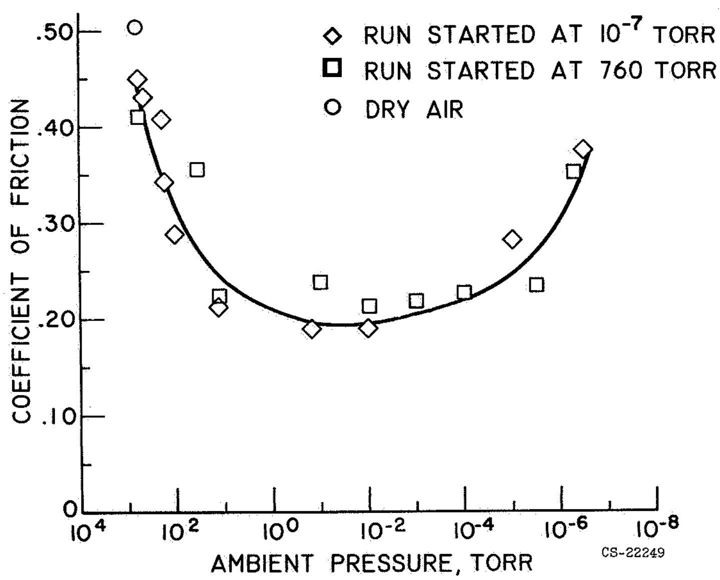


Figure 9(a). - Coefficient of friction for 52100 sliding on 52100 at various ambient pressures. Sliding velocity, 197 centimeters per second; temperature, 24° C.

E-3513

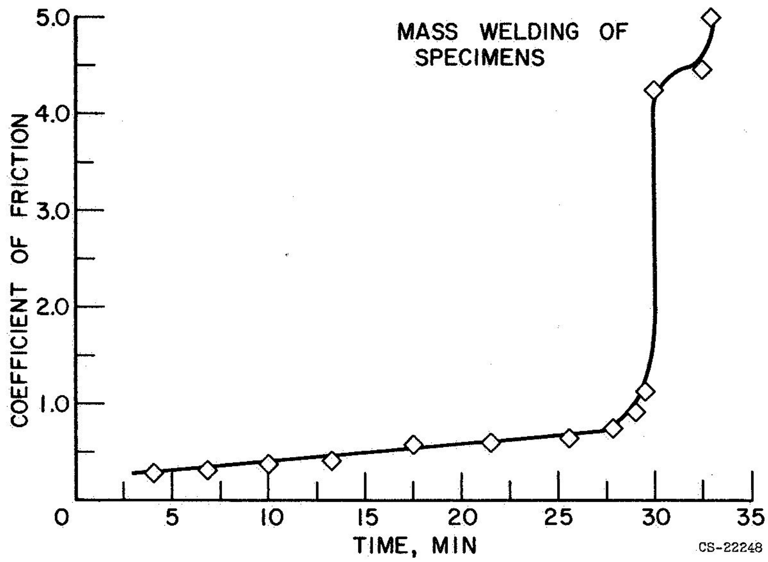


Figure 9(b). - Coefficient of friction for 52100 sliding on 52100 in vacuum with liquid helium cryogenic pumping; pressure, 10^{-7} Torr; sliding velocity, 197 centimeters per second; load, 1000 grams.

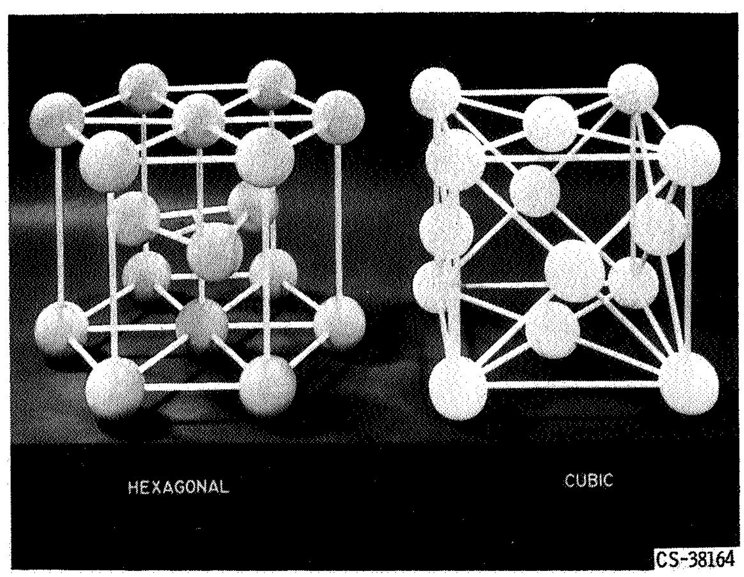


Figure 10. - Metallic crystal models.

E-3513

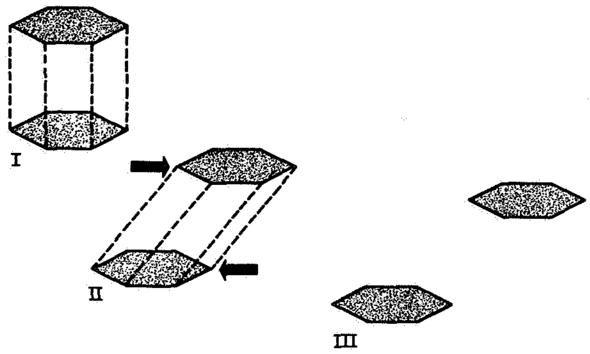


Figure 11. - Displacement of planes in hexagonal crystals with shear.

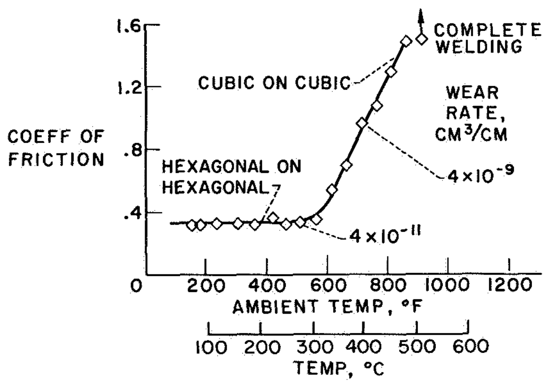


Figure 12. - Friction for cobalt sliding on cobalt in vacuum (10^{-9} Torr) at various temperatures. Load, 1000 grams; sliding velocity, 197 centimeters per second.

E-3513

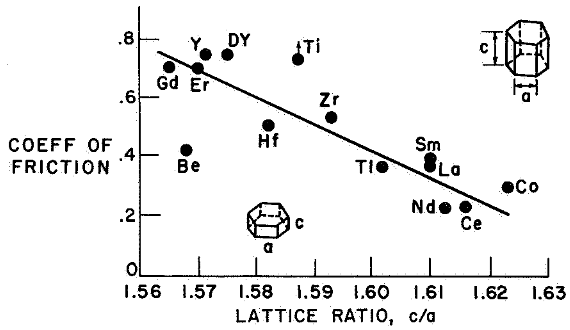
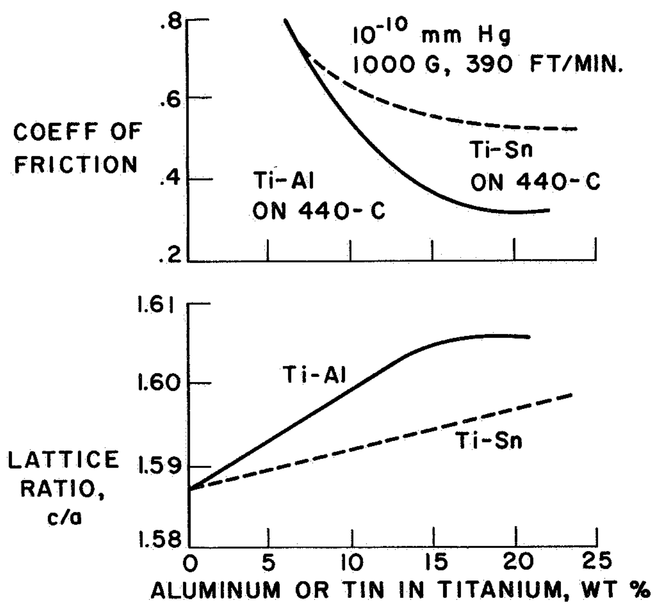


Figure 13. - Friction of various hexagonal metals on 440-C steel. Load, 1000 grams; sliding velocity, 197 centimeters per second; pressure, 10^{-9} Torr.



CS-38046

Figure 14. - Friction and lattice ratio (c/a) for titanium alloys. Load, 1000 grams; sliding velocity, 197 centimeters per second; pressure, 10^{-10} Torr.

E-3513

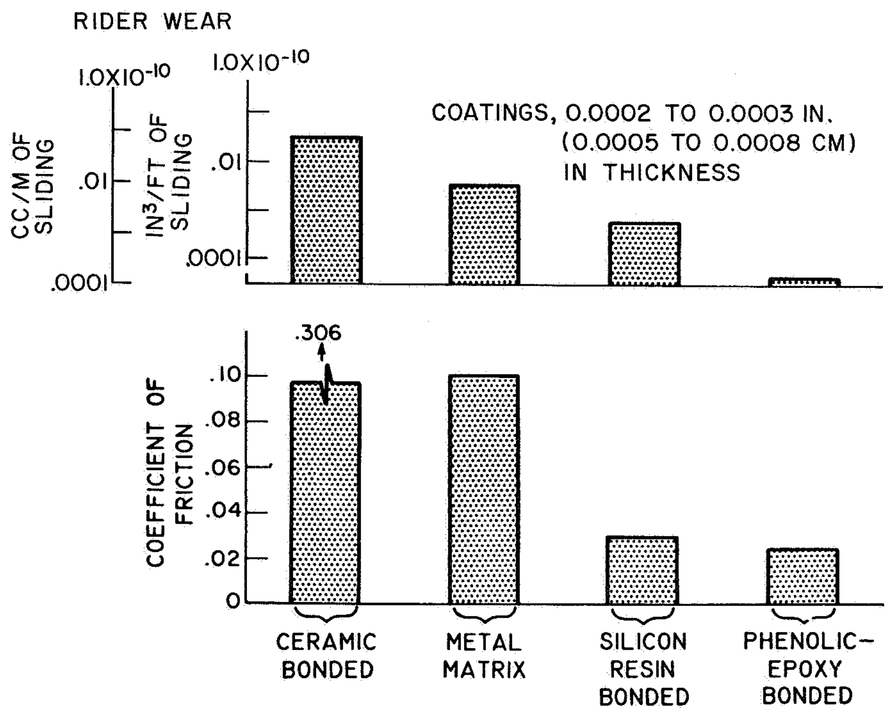


Figure 15. - Fricition and wear of 440-C on 440-C with various MoS_2 films. Ambient pressure, 10^{-6} Torr; sliding velocity, 197 centimeters per second; load, 1000 grams; duration of run, 1 hour.

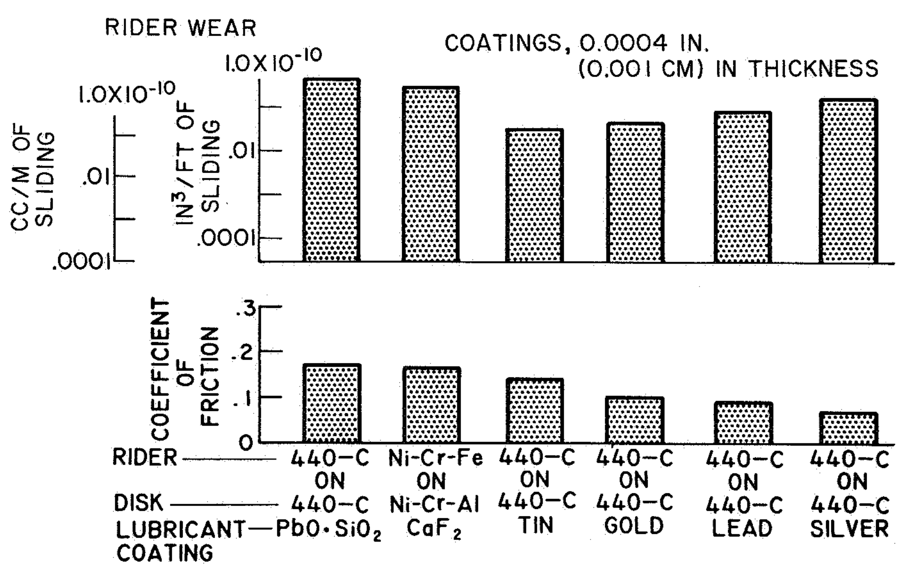


Figure 16. - Friction and wear of alloys with various coatings in vacuum. Ambient pressure, 10^{-6} Torr; sliding velocity, 197 centimeters per second; load, 1000 grams; duration of run, 1 hour.

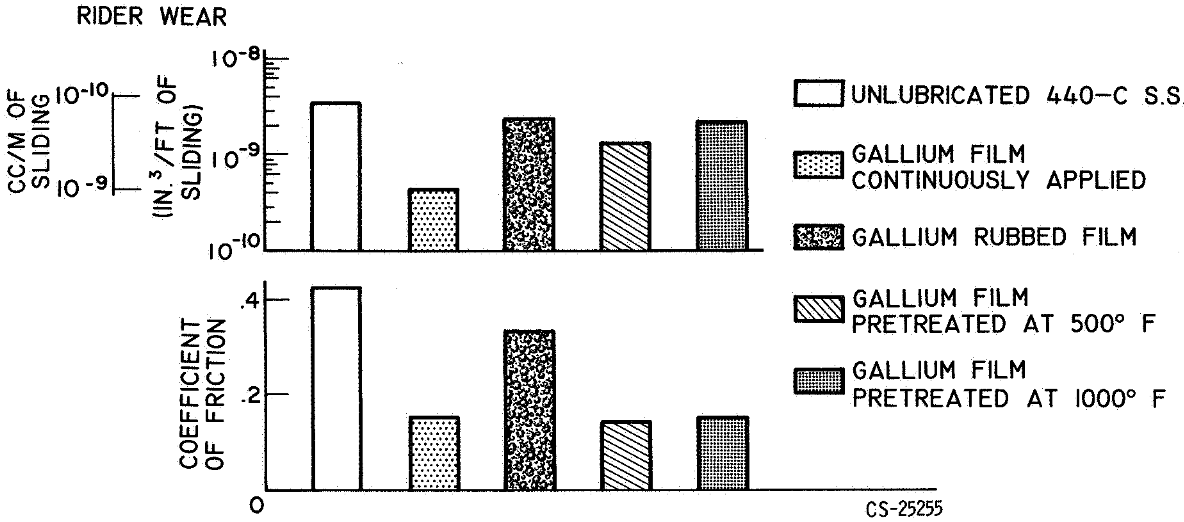


Figure 17. - Friction and wear of 440-C sliding on 440-C in air. Load, 1000 grams; atmospheric pressure; duration of run, 1 hour; 24° C (from ref. 18).

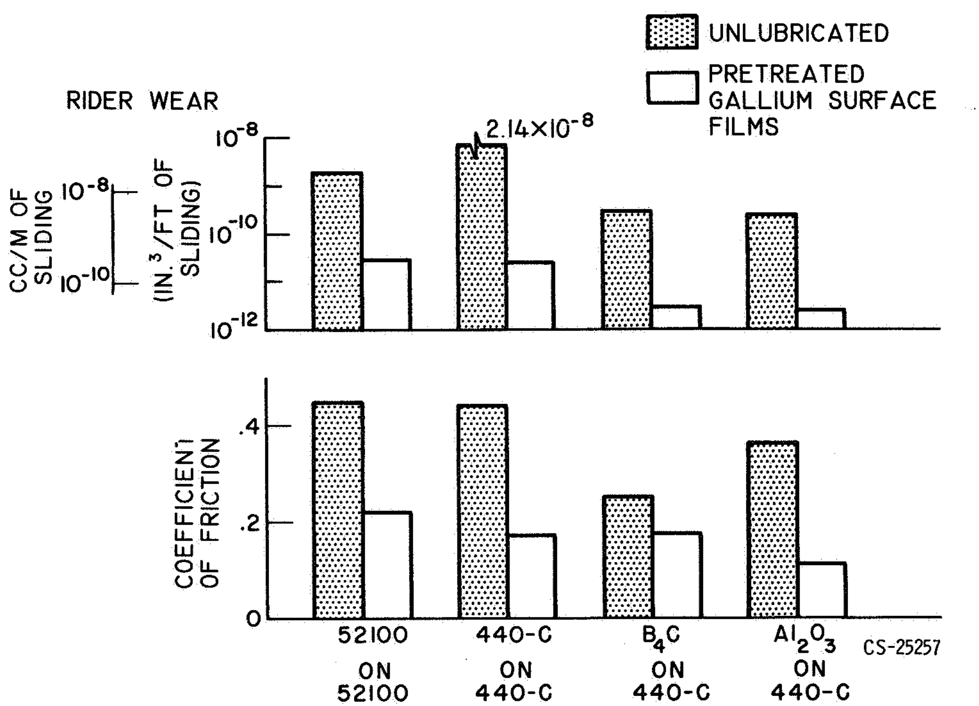


Figure 18. - Friction and wear of various materials in vacuum (10^{-8} Torr). Sliding velocity, 197 centimeters per second; load, 1000 grams; duration of run, 1 hour; liquid-nitrogen cryopumping.

E-3513

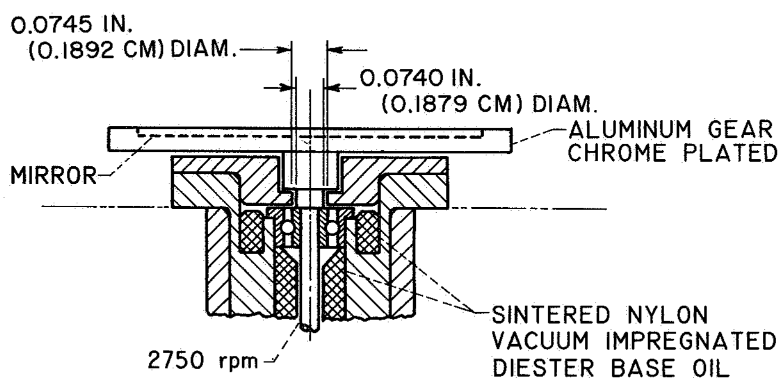


Figure 19. - Tiros II radiometer spindle assembly.